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THERMOELECTRIC GENERATORS AND MATERIALS: RADIATION EFFECTS, RELIABILITY, LIFETIME, AND FAILURE. AN ANNOTATED BIBLIOGRAPHY

Compiled by
E. GRAZIANO

SPECIAL BIBLIOGRAPHY
SB-61-60

JANUARY 1962

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Lockheed

MISSILES and SPACE DIVISION

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ABSTRACT

This literature search was conducted as part of research on the problems of using thermoelectric generators in space, which would directly convert heat from nuclear sources, into electricity. The purpose was to bring to light any information regarding reliability, lifetime, and mean time of failure of thermoelectric generators and materials due to oxidation, cracking, galvanic action, short circuits, radiation effects, and sublimation.

The results of the search indicate that almost nothing exists in the technical literature concerning lifetime and reliability of thermoelectric generators: for this reason, the scope of the bibliography was broadened considerably to include selected references to other thermoelectric devices and material when any mention was made of factors that might cause failure or malfunction.

The following sources were checked:

Applied Science and Technology Index, 1958 - date

Armed Services Technical Information Agency

Technical Abstract Bulletin, 1957 - date

Engineering Index, 1960 - date

Nuclear Science Abstract, 1948 - date

Radiation Effects Information Center, Accession List, 1957 - date

Physics Abstracts, 1930 - date

Electrical Engineering Abstracts, 1954 - date

Semiconductor Abstracts, 1955 - 1958

Solid State Abstracts, 1960 - date

U.S. Navy Research Lab., Status Report on Thermoelectricity,

NRL-MR 901, NRL-MR 1037, NRL-MR 1089, NRL-MR 1177

Thermoelectric Abstracts, 1959 - 1960

Direct Energy Conversion Literature, 1961

U.S. Government Research Reports, 1956 - date

Selenium and Tellurium Abstracts, 1959 - date

ABSTRACT

(cont'd)

Thermoelectric Materials for Power Conversion, QPR No. 3 and No. 7

Technisches Zentralblatt, 1959 - 1960

Technical Translations, 1960 - date

Barber, E., Thermionics and Thermoelectricity, Cal. Inst. Tech. Jet. Prop. Lab., Astro. Info. Lit. Search No. 294, Dec 1960, 185p.

Nagel, B.H., Annotated Bibliography on Thermoelectricity Materials and Devices. Autonetics, E.M. 5987, 28 Jan 1960, 225p.

Search completed August 1961.

1. Artman, R.A.

Effect of γ-IR-radiation on thermoelectric power of bismuth telluride.

AM. PHYS. SOC. BULL., v. 5, p. 168,

21 Mar 1960.

Abstract only of paper given at meeting of the American Physical Society, March 21-24, 1960 at Detroit, Michigan. "Measurements of changes produced in thermoelectric power and electrical conductivity of n- and p-type polycrystalline bismuth telluride and bismuth by γ-radiation from Co^{60} have been made. N-type samples measured in situ at room temperature show a thermoelectric power and conductivity which decrease with irradiation. The effect saturates at less than 6×10^6 r and anneals out in less than 3 hr. Near dry-ice temperatures the thermoelectric power increases with irradiation. The initial rate of increase is approximately 2% per 10^6 r. The increase anneals out with a half line of 29 hr at 230°K. Conductivity decreases approximately 1% for a dose of 6.8×10^6r. P-type samples near dry-ice temperatures show thermoelectric power also increasing with irradiation. The initial rate of increase matches that of the n-type. No data were taken on the annealing rate. The conductivity shows an increase of less than 0.2% for a dose of 25.2×10^6r. Generally irradiation has the same effect upon thermoelectric power as increasing the temperature. Bismuth shows no change in thermoelectric power near dry-ice temperature for a dose of 12.4×10^6r."

2. Aukerman, L.W.

Electron irradiation of indium antimonide and indium arsenide.

DISSERTATION ABS., v. 20, n. 2851,

Jan 1960. (PhD thesis, Purdue University, 1958)

The present work is concerned with the effect of electron bombardment on the electrical properties (Hall effect and conductivity) of two intermetallic semiconductors, indium antimonide and indium arsenide. 4.5 Mev electrons were employed in the bombardment. Hall coefficient and resistivity were measured as functions of temperature and bombardment flux. Various bombardment and annealing experiments are discribed and methods of analyzing the measurements in order to obtain useful information are discussed.

3. Balicki, M.

PRELIMINARY VERSION OF A METHOD FOR ASSAYING SUITABILITY OF THERMOELECTRIC SUBSTANCES FOR DIRECT CONVERSION OF FISSION TO ELECTRICAL ENERGY. General Electric Co., Knolls Atomic Power Laboratory, Schenectady, N.Y. Rept. no. KAPL-M-MXB-2, 21 Sep 59, 17p. (Contract W31-109-eng-52)

In order that irradiation testing be confined to the most promising materials, a reliable method is needed for arranging all candidate thermoelectric materials in order of their potential suitability for reactor service. A method is presented for discussion which apparently when fully developed promises not only to solve the problem of screening out the less attractive materials but also to reveal which of the materials screened are the best ones. The method is based on the vector addition of twenty parameters.

4. Biancheria, A., et al

THERMOELECTRIC NUCLEAR FUEL ELEMENT. Westinghouse Electric Corp., Atomic Power Dept., Pittsburgh, Pa. Second quarterly progress rept. AT(30-3)500; WCAP-1317, 10 Oct 59.

In-pile measurements of electrical resistivity of Bi_2Te_3 and GeTe are reported. The results are plotted as a function of the integrated neutron flux. For Bi_2Te_3, the electrical resistivity increased by approximately a factor of 5 over the irradiation cycle, and there was no evidence of leveling off. This behavior was found in the GeTe sample.

5. Blanke, B.C.

NUCLEAR BATTERY - THERMOCOUPLE TYPE.

Monsanto Chemical Co., Mound Laboratory,

Miamisburg, Ohio. Rept. no. CF-57-8-27;

Quarterly rept. no. 2, 30 July 57. (Contract

R-50-799965-sc-01-91)

One prototype thermoelectric generator was designed and built. This generator with 120 junction pairs was found unsatisfactory when tested because of breakdown of electrical insulation between the heat source and the junctions. Other designs and materials are being investigated.

6. Blanke, B.C.

NUCLEAR BATTERY - THERMOCOUPLE TYPE.

Monsanto Chemical Co., Mound Laboratory,

Miamisburg, Ohio. Rept. no. CF-58-4-49;

Quarterly rept. no. 5, 31 Mar 58. (Contract

R-50-799965-sc-01-91)

A third thermoelectric generator has been constructed and tested. Specifications for batteries having outputs of over six volts at power levels of 30, 50 and 1000 milliwatts at the end of six months have been made. An attempt was made to verify experimentally the theoretical equations of the Thomson and Peltier effects.

7. Blanke, B.C.

NUCLEAR BATTERY - THERMOCOUPLE TYPE.

Monsanto Chemical Co., Mound Laboratory,

Miamisburg, Ohio. Rept. no. CF-58-7-19;

Quarterly rept. no. 6, 30 June 58. (Contract

R-50-799965-sc-01-91)

7. (cont'd) A thermoelectric generator having independent outputs of 1.2 and 4.8 volts at more than 50 milliwatts after six month's service has been constructed and tested using a mock Po-210 heat source with an initial thermal power of 37 watts.

8. Blatt, F.J.

Effect of point imperfections on the

electrical properties of copper. II.

Thermoelectric power. PHYS. REV., v. 100

n. 2, p. 666-70, 15 Oct 1955.

The changes in the thermoelectric power of copper due to presence of interstitials and vacancies have been calculated in the free-electron approximation. It is found that the changes for concentrations of defects encountered in experiments on radiation damage due to massive charged particles are, at liquid nitrogen temperature, of the same magnitude as the absolute thermoelectric power of pure copper. Both interstitials and vacancies tend to reduce the absolute thermoelectric power of copper, and this effect should be readily observable in a suitably designed experiment. It is suggested that the effect may also be used to throw additional light on the processes which occur in the annealing of an irradiated sample. The calculated changes in the thermoelectric property of copper due to Frenkel defects are also of such magnitude as to make adequate precautionary measures necessary whenever the thermocouple, which is used to measure the temperature of the specimen, is also in the beam of the massive charged particles. Unless the thermocouple is suitably screened from the beam, unreliable temperature measurement is likely to result. Curves showing the predicted temperature and concentration dependence of the thermoelectric power change due to Frenkel defects are presented. The effect of small concentrations of arsenic in solid solution in copper on the thermoelectric power of copper has also been calculated by the same procedure. The calculated results are in satisfactory agreement with experiment, indicating that the results for interstitials and vacancies are probably of the correct magnitude.

9. Bloom, J.

13-WATT CURIUM-FUELED THERMOELECTRIC

GENERATOR FOR A SIX- MONTH SPACE MISSION.

Martin Co., Nuclear Div., Baltimore, Md.

Final rept., MND-P-2373, July 1960, 45p.

9. (cont'd) (Contract AT(30-3)-217)

The generator derives its power from the radioactive decay of the isotope Curium-242. Weight is about 16.6 pounds.

10. Breckenridge, R.G.
THERMOELECTRIC MATERIALS. Union Carbide Corp., Parma Research Laboratory, Parma, Ohio. BiMon. Progress rept. 4, Oct 1959, 33P. (Contract Nobs-77066)
ASTIA AD-231 650

Modification of the boron graphite/graphite system is being considered to improve the performance of the thermoelectric generator. A method of increasing the thermoelectric power by varying the concentration of boron along the length of the thermoelectric element is being studied. Liquid thermoelectric materials have advantages over solids, such as lower heat conductivities and freedom from radiation damage. Measurement of resistivity and thermoelectric power are to be made on the Cs-CsCl system since melting points and miscibility occur at lower temperatures than other alkali-alkali halide systems. Thermal conductivity: measurements which provide a direct determination of the anisotropy ratio were made on ATJ graphite samples from 1300° to 2000°K. Thermal conductivities of boronated graphite and porous graphite were also made. Work is continuing on the programming of the calculations of the integrals needed in the transport theory of graphite. A thermoelectric generator using boronated graphite against plain graphite and producing 50 mv over a range of 700° to 800°C was constructed by using elements 1/4 in. in diameter and 3 in. long.

11. A brief summary of research on radiation effects in solids. In PAPERS PREPARED FOR RADIATION EFFECTS REVIEW MEETING, CONGRESS HOTEL, CHICAGO. JULY 31-AUGUST 1, 1956. TID-7515, Pt. 2, del ., p. 5-100, 96p.

11. (cont'd) Research representative of work being done at Oak Ridge National Laboratory by the Solid State and Metallurgy Divisions is reviewed. Extensive graphic and tabular presentations are made of data from irradiations of Al-U alloys, stainless-steel-clad stainless steel-UO_2 dispersions, ThO_2-UO_2 ceramics, Si-SiC-UO_2 ceramics, Th, th alloys, Th-U alloys, Al-B_4C, B_4C ceramics and cermets, magnesium oxychloride cement, iron, steels, stainless steels, Ni, Ni alloys, BeO, Al_2O_3-Cr cermet, glasses, ZrO_2, HfO_2, zircon, Al_2O_3, MgO, SiC, quartz, ThO_2, steatite, forsterite, cordierite, spinel, lava, muscovite mica, BaO. TiO_2, TiO_2, and TiC-Nb-Ta. Radiation effects experience with thermocouples, electrical insulation, transformers, furnace and temperature control materials, bonded-wire strain gages and electric motors is briefly summarized. Work previously reported elsewhere is cited only by a literature reference. This presentation is not intended as a complete detailed coverage of ORNL work in the field.

12. Carter, F.L., et al

THERMOELECTRIC NUCLEAR FUEL ELEMENTS.

Westinghouse Electric Corp., Pittsburgh, Pa.

Quarterly progress rept. 1, 15 Nov 58, 67p.

(Contract AT(30-3)-500)

Thermoelectric design considerations; Preparation of mixed-valence thermoelectric materials; Thermoelectric property measurements; Physical and chemical characteristics of thermoelectric materials; Irradiation of thermoelectric materials.

13. Christy, R.W.

Electrical conductivity and thermoelectric

power in ionic crystals. AM. J. PHYS.,

v. 28, p. 457-461, May 1960.

Many of the most interesting mechanical and electrical properties of solids, especially at high temperatures or after radiation damage, depend on the presence of point defects -- interstitials and vacancies -- in the crystal lattice. Ionic crystals are especially suited for the study of these defects, because in them the defects are electrically charged. The ionic conductivity mechanism is reviewed, with reference to the information it yields about the properties of the defects. Recently, further information about the defects has been derived from the thermoelectric power (Seebeck effect) and these new developments are summarized.

14. Clark, R.A., Jr., Doncals, R.A., and Holman, R.R.
NUCLEAR THERMOELECTRIC POWER PLANT PROGRESS REPORT, MAY-AUGUST 1960. Westinghouse Electric Corp., Astronuclear Lab., Pittsburgh, Pa.
Rept. WANL-PR(A)001 3MW(e), 73p. Decl. 13 Jan 1961. (Contract NONR-3216(00))

The reference thermoelectric generator element was selected as one that will give an over-all conversion efficiency of 7 per cent for a practical generator, including allowance for contract losses and other assembly degradations. Preliminary hydraulic, thermal, and nuclear design analyses were used to establish a reference core for lifetime and control studies.

15. Corelli, J.C. and Frost, R.T.
Changes in the thermoelectric properties of PbTe, Bi_2Te_3 and ZnSb during irradiation.
Knolls Atomic Power Lab. BULL. AM. PHYS. SOC., SER. II, v. 5, p. 420(A), 25 Nov 1960.

An instrumented in-pile experiment previously described has yielded the following changes. The Seebeck coefficient of the n-type Bi_2Te_3 sample increased by $\simeq$10% during the irradiation while the resistivity was increased while the resistivity was increased by a factor of $\sim$2.8 with no significant changes for fast (> 1-Mev) flux times greater than $5 \times 10^{19} n/cm^2$. In the case of p-type ZnSb the resistivity increased by a factor of $\sim$12 with no large changes resulting beyond a fast flux time of $6 \times 10^{19} n/cm^2$. The p-type ZnSb converted to n-type after an accumulated fast flux time of $\sim 1.6 \times 10^{17}$ n/cm^2, and thereafter its Seebeck coefficient exhibited a gradual increase of $\simeq$15% with increased in-pile time. The resistivity of n-type PbTe increased in-pile time. The resistivity of n-type PbTe increased by a factor of $\sim$25 after a total accumulated fast flux-time of $1.2 \times 10^{20} n/cm^2$ with no large changes observed for fast flux-times greater than $\sim 6 \times 10^{19} n/cm^2$. Auxiliary experiments suggest that a significant part of resistivity increases for all samples because of stress-induced damage during reactor power transients. In some cases temperatures during irradiation were near the annealing threshold for PbTe and Bi_2Te_3.

16. Corelli, J.C., Frost, R.T. and White, F.A. Effect of reactor irradiation on thermoelectric properties of PbTe and Bi_2Te_3. AM. PHYS. SOC. BULL., v. 5, p. 168, 21 Mar 1960.

Abstract only of paper given at a meeting of the American Physical Society, March 21-24, 1960 at Detroit, Michigan. "Specimens of commercially available PbTe and Bi_2Te_3 have been irradiated at a temperature of $60 \pm 20^{\circ}C$ to a total flux-time of $1.0 + 0.3 \times 10^{19} cm^{-2}$ of neutrons having energy greater than 1 Mev. Duplicate samples irradiated with and without cadmium shields allowed a search for effects of transmutations caused by an integrated thermal neutron flux-time of $1.5 \pm 0.5 \times 10^{20}$ cm^{-2}. Preliminary comparison of Hall coefficients of irradiated and unirradiated n-type PbTe indicates a decrease in carrier concentration by a factor 4.5 ± 0.5. Seebeck coefficients at $30^{\circ}C$ of n- and p-type PbTe and n-type Bi_2Te_3 increased by factors of 1.8, 1.6 and 1.1, respectively, with no significant differences observable between cadmium shielded and unshielded specimens. The p-type Bi_2Te_3 (no initial impurity doping) exhibited an x-type Seebeck coefficient subsequent to the irradiation, and its magnitude was changed by a factor of 0.7 for the shielded and 1.8 for the unshielded specimen. The room temperature electrical resistivity of shielded and unshielded n-type PbTe increased by a factor of 10 as a result of the irradiation. Additional measurements of electrical resistivities and Seebeck coefficients at higher temperatures will be presented.

17. Corelli, J.C. and Frost, R.T. THE EFFECTS OF REACTOR IRRADIATION ON THE THERMOELECTRIC PROPERTIES OF LEAD AND BISMUTH TELLURIDES. General Electric Company, Knolls Atomic Power Laboratory, Schenectady, New York. Rept. no. KAPL-2091, 1 Apr 60. (Contract W-31-109-eng-52)

Commercially available specimens of polycrystalline n- and p-type lead telluride and n- and p-type bismuth telluride were irradiated in the Engineering Test Reactor at The National Reactor Test Station at Idaho Falls, Idaho. The preirradiation thermoelectric properties are compared to the postirradiation properties. Duplicate samples irradiated with cadmium shields allowed a search to be made of the effects of transmutations.

17. (cont'd) Total integrated flux-times of 1.5×10^{20} neutrons/cm^2(thermal) and 1.6×10^{19} neutrons/cm^2 (fast, i.e., for neutrons having energies greater than 1 Mev) are accumulated by the specimens during irradiation. The specimen temperature during irradiation was $60 \pm 20^{\circ}C$.

18. Cox, H.B.

The Cox Thermoelectric Generator for the conversion of heat directly into electrical energy. ELEC. ENG., v. 19, p. 383-385, 1 May 1895.

The thermoelectric generators described generate continuous current and are mechanically reliable, one having been in operation for three years without maintenance or any change in resistance. Absence of moving parts, relative quietness of operation and practical absence of maintenance problems would seem to be great advantages; on the other hand, great weight and limited output are considerable disadvantages. The pounds per horsepower ratio is of the order of 250 for the small generators and several times that for the large generator.

19. Danko, J.C., Kilp, G.R. and Mitchell, P.V.

IRRADIATION EFFECTS ON THERMOELECTRIC MATERIALS. (Presented at the ARS Space Power Systems Conference, Santa Monica, California, September 27-30, 1960) Paper no. 1276-60, New York, American Rocket Society, 1960, 8p.

The prime subject of a research and development program on a thermoelectric nuclear fuel element was $Li_xNi_{1-x}O$. In-pile measurements of the Seebeck coefficient and electrical resistivity were made at reactor ambient temperatures and elevated temperatures. In addition, preirradiation and post-irradiation measurements of the Seebeck coefficient, electrical resistivity, and thermal conductivity were performed. The following compositions were tested: $Li_{0.013}Ni_{0.987}O$ and $Li_{0.05}Ni_{0.95}O$. Postirradiation measurements on $Li_{0.013}Ni_{0.987}O$ samples after exposure to a total integrated thermal neutron flux of 1.4×10^{19} revealed that the electrical resistivity returned to the

19. (cont'd) preirradiation value; the Seebeck coefficient increased slightly; and the thermal conductivity remained essentially unchanged. In-pile measurements of the Seebeck coefficient and electrical resistivity of $Li_{0.05}Ni_{0.95}O$ at 464°C and up to 8 x 10^{18} nvt (thermal) did not show much variation from out-of-pile values.

20. Danko, J.C., et al

THERMOELECTRIC NUCLEAR FUEL ELEMENT.

Westinghouse Electric Corp., Pittsburgh, Pa.

Annual Progress Report. Rept. WCAP-1162,

15 Apr 59, 111p. (Contract AT(30-3)-500)

Reviews thermoelectric design considerations, preparation and thermoelectric properties of mixed valence materials; irradiation; fabrication; physical and chemical properties of thermoelectric materials; bonding and insulator studies; and measuring apparatus.

21. Deegan, G.E.

THERMAL AND ELECTRICAL PROPERTIES OF

GRAPHITE IRRADIATED AT TEMPERATURES FROM

100 TO 425°K. U.S. Atomic Energy Commis-

sion, Washington, D.C. Rept. SR-1716,

1956, 77p.

Data were obtained for the thermoelectric power and electrical and thermal conductivity of graphite as a function of several proton irradiations (0.65 - 30 μ ah/sq.cm.) from 103 to 423°K. In general, irradiating at 300°K produced the same property changes as irradiating at 103°K and then annealing to 300°K. For exposures greater than 5-10 μ ah/sq. cm., 423°K irradiations were appreciably less effective in producing property changes than 300°K. In pulse annealing of samples irradiated at 103°K, it was found that recovery of all properties was very marked at about 150°K and higher when room temperature was attained. In pulse annealing to higher temperatures the strong recovery state starting at about 400°K was attained. In comparing protron- with neutron-damaged samples, a correlation was found for the thermal and electrical conductivities but not for the thermoelectric power.

22. Dick, P.J. (ed)
SNAP PROGRAMS. Martin Co., Nuclear Div., Baltimore, Md. Quarterly progress rept. no. 4 for 1 July through 30 Sep 60, Tasks 2 and 3; MND-P-3012-I, 53p. (Contract AT(30-3)-217)

SNAP-1A: All ground handling equipment required to accomplish hot-cell welding of the fuel core closure seals, fuel core transportation, generator fuel core loading, and isotope generator handling was completed in manufacturing. Functional tests of this equipment to determine its conformance to prescribed ground handling procedures were initiated. Final assembly of the G-2 generator was completed and performance tests with an electrically heated source block were made. The generator was removed from the test chamber in preparation for vibration tests. Two Inconel X source containers for Ce^{144} fuel loading were machined and assembled. In addition, three practice cores for remote welding test purposes were fabricated. Dissimilar metal seals of stainless steel and aluminum for use at six closure areas between the G-3 generator inner and outer skins were completed. A pressure-tight seal was obtained at the stainless-steel-to-aluminum interface by ultrasonic welding. Evaluation and testing of high-temperature resistance electrical insulation coatings were accomplished for possible application to the G-3 generator stainless-steel hot skin. A Bureau of Standards A-418 ceramic film formulation showed good adherence at elevated temperature and satisfactory electrical resistance at room temperature. SNAP-III: SNAP III generator, 3M-1G-10 has completed 250 days of continuous life test operation. It has been operating since January 26, 1960. Power output was 1.96 watts (e) at the end of this reporting period compared with 2.25 watts at the beginning of this quarter and 3.45 watts at the start of life tests. Preparations were made to fuel SNAP III generator 1-G-5 with 2000 curies of Po^{210}.

23. Drabble, J.R. and Groves, R.D.
The effect of strain on the Seebeck coefficient of n-type germanium.
PHYS. & CHEM. SOLIDS, v. 12, p. 285-294, Feb 1960.

The effect of uniaxial strain on the Seebeck coefficient of n-type germanium has been studied in the temperature range where phonondrag effects are important. The changes in the Seebeck coefficient were found to be closely

23. (cont'd) correlated with the changes in the resistivity under the same conditions. The theory of the effect is discussed, and it is shown that the measurement of both these changes leads in a fairly direct was to an estimate of the anisotropy of the phonon-drag part of the Peltier tensor for a single valley. Results are presented and analyzed for a number of specimens.

24. Eartherly, W.P. and Rasor, N.S.

THE THERMOELECTRIC POWER OF GRAPHITE; DEPENDENCE ON TEMPERATURE, TYPE AND NEUTRON IRRADIATION. North American Aviation, Inc., Downey, Calif. SR-196, 1952, 28p.

The thermoelectric power (q) of nine grades of artificial and natural graphite was measured in the temperature region 4.2 -300°K. The effect of neutron exposure on the temperature dependence in this interval was determined also. An analytical expression for q was derived that is in excellent qualitative agreement with the experimental data. Q is a reliable measure of the number of conduction electrons. The variation observed among grades of graphite is similar to the effect produced by slight changes in the number of conduction electrons. This variation in grade is correlated with particle size.

25. Flanagan, T.P.

The effect of nuclear radiation on materials. J. ELECTRONICS AND CONTROLS, v. 6, p. 337-46, Apr 1959.

The principles underlying the effects of nuclear radiations on materials are outlined. Practical examples are used to illustrate these principles.

26. Fritts, R.W.

Thermoelectric generator element design. In WHIRLPOOL THERMOELECTRIC SYMPOSIUM. Proceedings, St. Joseph, Mich., Whirlpool Corp., p. 147-164, 1959.

26. (cont'd) Presents the state of the art as it applies to thermoelectric generation, particularly where lead telluride is used. This is done by characterizing the problems which confront the design engineer in fitting lead telluride thermoelectric generator elements into structures that he wants to build, and predicting their performance.

27. Frost, R.T., Correlli, J.C., and Balicki, M.
Reactor irradiation of PbTe, Bi_2Te_3, and
ZnSb. Knolls Atomic Power Lab. BULL. AM.
PHYS. SOC., SER II, v. 5, p. 420 (A),
25 Nov 1960.

Instrumented samples of polycrystalline n-type PbTe and Bi_2Te_3 and p-type SnSb have been irradiated in the Engineering Test Reactor (ETR) to a total integrated flux-time of $1.2 \cdot 10^{20}$ cm^{-2} of neutrons having energies greater than 1 Mev. The corresponding thermal flux time was $6.1 \cdot 10^{20} cm^{-2}$. Electrical resistivity and Seebeck coefficient were monitored by means of seven lead attached to each of the three samples, which were located within a cylindrical region in the reactor 1/2 in. long and 3/4 in. in diameter. Thermal and resonance neutron reactions on tellurium produced iodine approaching the amount used in the initial doping of the n-type materials. Gamma-ray spectroscopy on uninstrumented sampled irradiated to comparable flux-times failed to disclose lines due to long-lived daughters of fast neutron-induced reactions. The changes in electrical properties of uninstrumented PbTe and Bi_2Te_3 samples induced by a fast (> 1-Mev) neutron flux time of $1.5 \cdot 10^{19} cm^{-2}$ are essentially completely annealed in the range of temperature from 170° to 190° C, respectively.

28. Gaidos, F. and Glick, H.L.
INSULATION RESISTANCE OF THERMOELECTRIC
MAGNESIA INSULATED CHROMEL-ALUMEL THERMO-
COUPLES. Westinghouse Electric Corp.,
Atomic Products Dept. WAPD-S5W-EP-23,
WAPD-1-6, n.d.

Experiments were performed to determine the functional properties of the thermocouple in high temperature and high neutron density environments. The experiments were performed at Bettis and in the active lattice of the Materials Testing reactor (MTR), Arco, Idaho.

29. General Electric Co., Aircraft Accessory Turbine Department, Syracuse, N.Y. MATERIALS RESEARCH AND DEVELOPMENT FOR THERMOELECTRIC POWER GENERATION Progress rept. 1, 25 July 60, 5p. (Contract DA44-177-TC-639)

Several lines of work have been started for the purpose of obtaining pertinent information on the preparation of stoichiometric $CuGaTe_2$ as a thermoelectric semiconductor. Experiments directed towards learning more about the chemical nature of $CuGaTe_2$ were therefore initiated. Of ma or interest in this connection was the determination of the rate of weight loss of $CuGaTe_2$ as a function of temperature, and of the dissociation pressure of tellurium over $CuGaTe_2$. The results of these experiments are being used to devise the most suitable method for the preparation of new samples. Electrical measurements of thermal conductivity as a function of tellurium deficiency were initiated.

30. General Electric Co., Aircraft Accessory Turbine Department, Syracuse, N.Y. MATERIALS RESEARCH AND DEVELOPMENT FOR THERMOELECTRIC POWER GENERATION. Progress rept. 2, 25 Aug 60, 4p. (Contract DA44-177-TC-639)

Work on the rate of tellurium loss in $CuGaTe_2$ at high temperatures and its effect on its semiconducting properties was continued.

31. Gross, L.W. SNAP III - THERMOELECTRIC GENERATOR ENVIRONMENTAL TEST. Martin Co., Nuclear Division, Baltimore, Md. Rept. P-2101, Aug 59, 68p.

31. (cont'd) The effects of simulated space vehicle vibration, acceleration, and shock on the operation and efficiency of a SNAP-III thermoelectric generator are described. The test specifications were developed by Jet Propulsion Laboratories for the third stage and payload of the Vega vehicle.

32. Gross, L.W.

SNAP III- THERMOELECTRIC GENERATOR ENVIRONMENTAL TEST. VOLUME II. Martin Co., Nuclear Div., Baltimore, Md. MND-P-2101-II, Oct 59, 50p. Decl 21 Sep 60.

The thermoelectric generator operated for about 250 hours during the entire test program. The efficiency varied 5% of the total performance during the vibration cycle, and remained relatively stable during the acceleration and shock tests. Recovery was complete in all cases. Oscillatory d-c superimposed on the d-c output of the generator was observed during the shock and vibration tests, and disappeared when the environmental forces were discontinued. The maximum d-c ripple was 7.4 millivolts rms in the y-Plane during the shock and vibration cycles. It was concluded that SNAP III thermoelectric generator No. 1G5 is reliable in environments simulating the WS-117 L Vehicle.

33. Gross, L.W. and Schramm, E.J.

SNAP III- THERMOELECTRIC GENERATOR ENVIRONMENTAL TEST. VOLUME III. Martin Co., Nuclear Div., Baltimore, Md. MND-P-2101-III, Jan 60, 73p. (Contract AT(30-3)-217)

The results of tests on four thermoelectric generators (two each of two different configurations) of the Snap III type to both the J.P.L. and the L.M.S.D. specifications for shock, vibration, and acceleration test are reported. The simulated levels were based on the anticipated environments of the Vega (J.P.L.) and WS117L (L.M.S.D.) systems. All four generators exhibited the same characteristic behavior pattern throughout the vibration portion of the test program, showing a d-c ripple in the generator output only in the Y plane. This behavior of the generator is attributed to the oscillatory change in internal resistance resulting from vibratory elastic deformation of the thermoelectric elements. This produces a transient in the electrical output with a resultant reduction in generator efficiency.

33. (cont'd) The maximum reduction in efficiency was noted in the 700 cps region. A resonance on the generator shell at 1845 cps was noted, but generator electrical output and efficiency were not affected. Upon discontinuance of the induced vibration, the generators returned to normal operating conditions. While undergoing shock test, a d-c transient was noted at the time of impact, resulting in a slight decrease in efficiency. The generators immediately returned to their normal operating efficiency. In the acceleration portion of the test no d-c transient was evident in any of the three planes, therefore the generator efficiency remained constant. Steady state conditions were re-established at the start of each new test phase (i.e., changing planes of excitation, changing from shock to vibration, etc.) Thus, any variation from pretest efficiency was attributed to the external load resistance becoming unmatched due to the change in internal resistance. The important result is that complete generator recovery was consistent in all cases and normal operation continued. The generator, shell, internal structure and pressure, and the hot and cold junction temperature were not affected during the test. As a result of this test program, it was concluded that the Snap III thermoelectric generator will operate reliably in the environments associated with the Vega and WS117L vehicles.

34. Harvey, R. and Bowes, W.M. (eds)
SNAP PROGRAMS. Martin Co., Nuclear Div.,
Baltimore, Md. Quarterly progress rept.
no. 4 for 1 July through 30 Sep 60,
Subtask 5.3 and Task 6; MND-P-3012-II,
170p. (Contract AT(30-3)-217)

Generator 2A, the design of which was completed last quarter, was fabricated and electrically tested. The generator met all significant design requirements with the exception of the collector work function. During the preparations for environmental tests one of the leadthroughs failed. Metallographic examination revealed that it is necessary to make some design revisions of the leadthrough. Generator 2A was an experimental unit which led to the design of generator 2B. Specifically, the conclusions obtained from 2A confirmed certain processing methods applicable to future units. The latter unit includes provisions for remote control fueling and its operation should attain anticipated performance characteristics (P_o, η , w, ϕ_c, T_e, T_c and life). Critical areas of design, construction, and processing of 2B include the facility for remote control fueling, the attainment of close interelectrode spacing and low collector work function, and the achievement of a rugged generator. Accordingly, a vigorous theoretical and experimental approach was undertaken. A life test on generator 1A was initiated and over 21 hours of operating time was accumulated. The emitter was not aged prior to incorporation into the generator; as a result, the evaporation of barium from the

34. (cont'd) emitter eventually reduced the diode internal resistance to the point where it was no longer feasible to continue the life test. The procedures for fueling a thermionic generator with a Cm^{242} heat source were established. An activation device in which a work function of approximately 1.9 volts was achieved was designed, fabricated, and tested. These same techniques can be incorporated in a practical generator design. Following this test, the preliminary design of generator 2B was established, and development on the design was initiated. To date, considerable progress has been made in the development of purification processes for gram quantities of americium and curium. Design, fabrication, and installation of experimental equipment for producing capsules for irradiation, for processing the capsules after irradiation, and for testing containment materials has been completed, and the equipment is in operation. The processes involved are being rigorously evaluated in preparation for the construction of prototype systems. Nuclear, thermal, and hazards analyses were undertaken on all phases of this task; results appear quite satisfactory.

35. Honeywell Research Center, Hopkins, Minn.
DEVELOPMENT OF A SEMICONDUCTOR FILM-TYPE THERMOCOUPLE ENERGY CONVERTER. Quarterly technical rept. no. 5, 1 Oct 60 - 1 Jan 61, 18p. (Contract DA 11-022-501-ORD-3230, Proj. TN2-8106)

Effort was directed toward the fabrication of a plasma-sprayed Li20-doped Ni0 generator. Cracking of the alumina substrate during flame spraying necessitated a change in the design of the plates. Voltages of less than 25v per plate were obtained. Attempts will be made to improve the output voltage and retain the original 5 or 6 plate generator design; however, 8 or 9 plates can be used which would occupy slightly more than half of the 25 cu in. allowed. Because of the difficulties encountered with the A design, no attempt will be made to fabricate generators of designs B or C. Design computations for a cylindrical generator C are presented. These calculations indicate that a cylindrical-designed 25-cu in. oxide thermoelectric generator operating with a hot end temperature of 1300 C and a cold end temperature of 600 C would generate 3.0 w.

36. Horne, R.A.
Effect of oxide impurities on the thermoelectric powers and electrical resistivities of

36. (cont'd) bismuth, antimony, tellurium and bismuth-tellurium alloys. J. APPL. PHYS., v. 30, p. 393-397, Mar 1959.

The thermoelectric powers of bismuth and antimony are only slightly altered by the presence of Bi_2O_3 and Sb_2O_3 respectively, and the electrical resistivities are increased. The thermoelectric power of tellurium, however, is extremely sensitive to TeO_2 impurities. Bismuth tellurium alloys show greatest sensitivity to oxide impurities when their composition is in the range corresponding to Bi_2Te_3. The thermoelectric powers of these materials depend in detail on the manner in which the thermal gradient is applied during measurement.

37. Howe, J.T. (ed)
SOLID STATE DIVISION QUARTERLY PROGRESS REPORT FOR PERIOD ENDING NOVEMBER 10, 1952.
Oak Ridge National Lab., Tenn. Rept. no. ORNL-1429, 4 Mar 53, 57p. Decl. 12 July 1960.
(Contract W-7405-eng-26)

Previously reported large creep rates in Inconel were s own to be a result of erratic behavior of microformer transducers. Several coil-spring type transducers were fabricated and tested. Impact tests were made on irradiated carbon steel. A program of tests was initiated to determine radiation effects on bonded-wire resistance strain gages. Reactor fuels Nos. 21 and 27 ($NaF-KF-ZrF_4-UF_4$ and $NaF-ZrF_4-UF_4$, respectively) were irradiated in Inconel capsules. A dynamic-corrosion apparatus for the Materials Testing Reactor (MTR) was designed. Hardness measurements were plotted against penetration distance for aluminum bombarded with 100 a/hr of 21-Mev protons. A method is proposed for in-pile determinations of dielectric constant and attenuation factor of insulators in cables. Design and fabrication of equipment for remote metallographic specimens were completed. Radiation effects on thermocouples are reported. Nuclear-heat generation in type 347 stainless steel was measured. Neutron spectra in the Bulk Shielding Facility were investigated. Fast-neutron bombardment of diamond, quartz, and cubic SiC produced a continuing lattice expansion. Thermally unstable radiation-produced disorder is retained by germanium at -78°C. Irradiation of germanium showed that there is a continuous decrease in resistivity and Hall coefficient with decrease in temperature. Data are reported on annealing of KCl F centers and radiation stability of plastics and elastomers.

38. Jamison, R.E. and Blewitt, T.H.

Behavior of two types of thermocouples under pile irradiation at low temperatures.

REV. SCI. INSTR., v. 24, p. 474, June 1953.

Both Cu-constantan and Fe-constantan thermocouples were tested in groups of three each in a liquid-N_2 bath placed in the Oak Ridge X pile. The test ran for 60 hours, giving a net integrated fast flux of $5\ 10^{16}$ nvt. The emf, corrected to constant pressure of the liquid N_2, remained constant $\pm$ 0.01 mv throughout the test. The warm junction being at ice temperature, the emf of the three Cu-constantan couples averaged 5.43 mv, while those of the three Fe-constantan couples averaged 7.72 mv. It should be noted that failure of the lacquered glass insulation on the thermocouples caused grounding to the Al Dewar, invalidating readings from Fe-constantan couples during the last 8 hours and making readings from the Cu-constantan couples intermittent during the last three hours of testing.

39. Kach, A.

Zur frages des wirkungsgrades thermoelektrischer generotoren. (On the question of efficiency of thermoelectric generators).

ELEKTROTECH. Z., v. 78, p. 182-187, 1 Mar 1957. (In German)

Translation no. 58-1095 available from SLA Translation Center, Crerar Library, Chicago, Illinois. The T-E generator is the simplest arrengement for converting heat to electrical energy. There are no moving parts, only slight wear, great reliability, it requires almost no servicing and from this it would be preferably suitable also for the conversion of large quantities of high grade energy.

40. Kelvin, W.T.

On the effects of mechanical strain on the thermoelectric qualities of metals.

In MATHEMATICAL AND PHYSICAL PAPERS,

v. II, p. 173-174, Cambridge, University

40. (cont'd) Press, 1884.

Brief description of experimental investigation of thermoelectric effects of mechanical strains.

41. Kerr, D.L. and Gessner, R.L.
MINIMIZING THE WEIGHT OF THERMOELECTRIC GENERATORS IN SPACE APPLICATIONS. Presented at the AIEE Summer and Pacific General Meeting and Air Transportation Conference, Seattle, Washington, June 21-26, 1959. AIEE Paper CP 59-937.

The importance of reliability and weight as performance criteria for equipment to be used in space vehicles is stated. The inherent potential advantage of a thermoelectric generator and other static devices from the standpoint of reliability is pointed out. The need is indicated for making weight estimates of thermoelectric generator systems on a consistent basis for purposes of evaluation and direction of future work. A thermoelectric generator system for providing auxiliary power for space vehicles is defined, and some discussion is given of the role of efficiency in weight minimization. Finally, an approach for predicting and minimizing the weight of a thermoelectric generator is briefly outlined and results of a number of calculations using this procedure are presented.

42. Kilp, G.R., et al
THERMOELECTRIC NUCLEAR FUEL ELEMENT. Westinghouse Electric Corp., Atomic Power Department, Pittsburgh, Pa. Progress rept. 19; WCAP-1380, 10 Feb 60, 23p. (Contract AT-(30-3)-500)

Higher as-pressed pellet densities were achieved by introducing double-end pressing action. Binary and ternary uranium compounds were prepared and pelletized using the double action. A new bonding eutectic is being tried for establishing good electrical contact between steel end disks and the pellets. Numerous electrical measurements were carried out on materials

42. (cont'd) involved in irradiation and fabrication studies. Data are presented from irradiation studies of a ZnSb sample and samples of GeTe and PbTe. Inpile results are described for a series stack of annular PbTe wafer heated by fission of UO_2 packed in the core of the stack of wafers. Other experiments are underway at the Brookhaven reactor. Fabrication studies described include swaged PbTe, compatibility of PbTe with various cladding materials, a bench-test of rod-type PbTe, and a p-n-couple demonstration device.

43. Kilp, G.R., et al

THERMOELECTRIC NUCLEAR FUEL ELEMENT.

Westinghouse Electric Corp., Atomic Power Department, Pittsburgh, Pa.

Rept. WCAP-1513, Progress rept. 20, 10 Mar 60, 15p. (Contract AT (30-3)-500)

Thermoelectric measurements were made on USe_x, UTe_x, and US_x, n-p junctions of PbTe and $Bi_{0.05}Ge_{0.95}Te$, and swaged elements. Mild steel and electrolytic iron exhibited best results to date for end caps. Results for an inpile device consisting of a swaged couple of n-type PbTe and p-type $Bi_{0.1}Ge_{0.9}Te$ with a rod heater at the center are reported. The thermal conductivity and Seebeck coefficient remained stable while the resistivity increased. The irradiation of $Li_{0.06}Ni_{0.94}O$ at 400°C and p-type PbTe at 375°C produced little change in their properties.

44. Kilp, G.R.

THERMOELECTRIC NUCLEAR FUEL ELEMENT.

Westinghouse Electric Corp., Atomic Power Department, Pittsburgh, Pa.

Rept. WCAP-1580; Progress rept. 23, 10 June 60, 27p. (Contract AT(30-3) -500)

A 200-channel digital voltmeter was placed in operation. Swaged couples of p- and n-type PbTe were prepared. A $Li_{0.06}Ni_{0.94}O$ sample irradiated at 400°C exhibited little radiation effects. A sample of p-type PbTe, irradiated at 373°C, exhibited a slight increase in Seebeck coefficient and a doubling of

44. (cont'd) the value of the electrical resistivity. The cold pressing characteristics of n- and p-type PbTe powders, and heat treating characteristics of the n-type, were studied. Swaging trials on n- and p-type PbTe at 20 and $< 300^{\circ}C$ showed a temperature effect on uniformity of thickness of clad and core rod. A die was designed for pressing annular pellets of thermoelectric materials.

45. Kilp, G.R., et al

THERMOELECTRIC NUCLEAR FUEL ELEMENT

QUARTERLY PROGRESS REPORT - JULY - SEPTEMBER, 1960. Westinghouse Electric Corp., Atomic Power Dept., Pittsburgh, Pa.

10 Oct 60, 55p. (Contract AT-(30-3)-500)

Seven binary and ternary uranium chalcogenides were prepared for melting in helium-filled tantalum bombs. The USTe material is to be swaged into a test device for thermoelectric measurements. Commercial purity PbTe is being processed in a graphite-steel bomb to learn if it can be used to realize substantial cost savings. Property measurement results are listed for various telluride thermoelectric materials and elements, and for various devices for irradiation evaluations. Life tests of PbTe elements have been running for 1700+ hr. Results are analyzed for a Westinghouse Testing Reactor (WTR) irradiation test sample. Preinstrumentation techniques were developed to improve the amount and quality of information being secured from swaged elements under test. Calculations were made on thermal cascaded thermoelectric elements, and powder metallurgy dies for producing such elements were procured. Results of compatibility studies of PbTe and GeTe with various structural materials were reported. Data were obtained for the Case II thermoelectric reactor core designs. The design features high-enrichment fuel, a Be-UO_2 fuel matrix with a Cu-Fe inner electrical conductor and an aluminum outer conductor. Work began on the evaluation of a low-enrichment (Case III) design.

46. Kilp, G.R., et al

THERMOELECTRIC NUCLEAR FUEL ELEMENT,

QUARTERLY PROGRESS REPORT FOR OCTOBER-DECEMBER 1960. Westinghouse Electric Corp., Atomic Power Dept., Pittsburgh, Pa.

10 Jan 61, 63p. (Contract AT (30-3)-500)

46. (cont'd) Materials prepared for evaluation of thermoelectric properties included PbTe, USe, and USTe. The life test of hot-swaged PbTe has exceeded 4300 hr. Thermal conductivity values were obtained for a Lavite sample. A swaged PbTe couple featuring dual doping levels of the thermoelectric materials for thermal cascading was tested. An operating efficiency of 5.36% was achieved with a PbTe element featuring a major decrease in clad resistance. A metallographic study of swaging of PbTe is presented. Latest data on compatibility of thermoelectric materials with cladding materials indicate that W, Al, and possibly, Cr are the most nearly compatible materials tested with $Ge_xBi_{1-x}Te$. Design considerations are listed for a thermoelectric fuel element in which the hot junction temperature is a constant value independent of reactor power distribution.

47. Lambert, J.B.

BEHAVIOR OF S.I.R. FUELS IRRADIATED IN SODIUM (SPECIAL REQUEST KAPL-79: THE "BETA EXPERIMENT"). Final rept. on Production Test, 105-180p., HW-25330, Del., 12 Aug 52, 119p.

Irradiations of fuel materials and coil springs for the Submarine Intermediate Reactor were performed in dry process tubes in a Hanford pile. The fuel specimens and controls were in capsules of Na, and temperature of the fuel was maintained at 450°C when feasible. The coil springs were in He gas at 350°C, and were under compression during irradiation. Eleven of the capsules contained fuel in the form of enriched U metal or oxide. Five control capsules contained natural or depleted U metal. Nine metallic fuel specimens were in direct contact with the Na, whereas eight of the metallic or oxide fuel specimens were sealed in tubes of Zr, Ti, Fe, or type 347 stainless steel which were immersed in Na. Total irradiations varied from $1.3\ 10^{19}$ to $4\ 10^{20}$ n/cm^2. Handling of the materials at Hanford and the conditions of irradiation are discussed. Data are tabulated on performance of heaters and thermocouples. No data from post-irradiation investigations of the materials are included.

48. Leifer, H.N., et al

Galvanomagnetic and thermomagnetic effects in PbTe. AM. PHYS. SOC. BULL, v. 4, p. 362, 27 Aug 59.

48. (cont'd) In an attempt to understand the scattering mechanisms in PbTe and similar semiconductors, magneto-resistance, thermomagnetic resistivity, Hall and thermoelectric measurements have been carried out in the temperature range of 300°K to liquid helium.

49. Levy, R.A.

Radiation effects on thermoelectric power in Bi_2Te_3. AM. PHYS. SOC. BULL, v. 5, p. 168, 21 Mar 60.

Abstract only of paper given at meeting of the American Physical Society, March 21-24, 1960, at Detroit, Michigan. "Samples of n-type Bi_2Te_3 obtained from Merck, Inc., have been bombarded with 2-Mev electrons from a Van de Graaff accelerator in beam currents ranging from 1 to 85μ a. Total dosages ranged up to 100μ amp-hr. Thermoelectric power and resistivity measurements were made before, during, and after radiation by means of standard dc techniques using Chromel-Alumel thermocouples. Thermoelectric power decreased up to 50 per cent during bombardment and recovered afterward. Temperature effects prevented an adequate determination of the effect of radiation on electrical resistivity. Other than surface oxidation or melting from the high temperatures produced by the bombarding electrons, no permanent effects were observed in the samples. All measurements were made on flat rectangular wafers sliced parallel to the axis of poly-crystalline cylindrical ingots."

50. Lightweight thermoelectric generator developed by General Instrument Corp.

GAS AGE, v. 125, p. 26, 14 Apr 60

Small power plant can produce electricity for a year on 200 lb. of propane, or about 43 therms of natural gas equivalent.

51. Lingle, J.T. C

AUXILIARY POWER SUPPLY FOR SURFACE LAUNCHED MISSILES (U). Minneapolis-Honeywell Regulator Co., Hopkins, Minn. Final progress rept. 15 Oct 60 - 14 Mar 61, 14 Mar 61, 72p. (Contract NOw 60-0031)

51. (cont'd) CONFIDENTIAL REPORT

Descriptors: Guided missiles, Auxiliary power plants, *Power supplies, Generators, Design, Combustion chambers, Heat transfer.

52. Lomer, W.

THE DIRECT CONVERSION OF BETA-IRRADIATION INTO LOW-VOLTAGE ELECTRICAL ENERGY. Atomic Energy Research Establishment, Harwell, Great Britain. Rept. AERE-T/M-108, Apr 54, 16p.

A theory is presented with accounts for the American observations on the emf produced by a semiconductor junction under irradiation. It is shown that for high efficiency a semiconductor with a large energy gap, and with both p and n material as heavily doped as it is practical, should be placed in a very high irradiation density. The optimum thickness for the transistor is found to be when both p and n material are one or two diffusion lengths thick. Figures are given for possible efficiencies of Si and Ge, and show the former far better if it can be produced in suitable form. The lifetime of the battery will be determined by atomic displacements caused by the irradiation, and is a serious limitation. Any practical use would necessitate a compromise between long lifetime and high efficiency, which require respectively low and high irradiation density.

53. McCollum, P.A.

UNCONVENTIONAL ELECTRICAL POWER SOURCES. Oklahoma Agricultural and Mechanical Coll., Instit. of Tech., Stillwater. Project no. 6058; PB-151726; WADC-TR-54-409(Pt.III), Sep 56, 111p. (Contract AF33(616)-2237)

Research directed toward gaining additional information concerning the theoretical and practical limitations and capabilities of generating electrical power by means other than rotating machinery and conventional batteries is described. Data and theory are presented on the oscillating generator utilizing permanent magnet excitation, the variable reluctance oscillating generator, metal thermopiles, the fuel cell, p-n junction silicon solar cell, and nuclear converters.

53. (cont'd) Results of laboratory experiments are presented on the permanent magnet oscillating generator, the variable reluctance generator, metal thermopiles, and the silicon solar cell. Efficiency of energy conversion, weight and size per unit power output, range of voltage and current, life and reliability were emphasized.

54. McCormick, J.E.

PERFORMANCE OF THE TAP-100 THERMOELECTRIC CONVERTER. Rome Air Development Center, Griffiss Air Force Base, N.Y. Rept. no. RADC TN 61-26; Proj. 6185, Apr 61, 14p.

ASTIA AD-257 312

Design and fabrication data are presented on the TAP-100 thermoelectric converter. Details of performance of the equipment are included. The device was operated to failure with the test program being divided into three parts as follows: (1) a preliminary evaluation during which a number of short runs were conducted so that loading and fuel consumption data could be obtained for various hot junction temperature levels, (2) a life test of the device, and (3) final testing, conducted just prior to disassembly. After testing the device was disassembled and the failure mechanics analyzed. Results indicated failure was caused by a combination of numerous internal shorts and severe junction breakdown.

55. Mackintosh, I.M.

Photon-radiative recombination in PbSe, PbTe, and PbS. PHYSICAI SOCIETY PROCEEDINGS, v. 69B, p. 115-18, 1956.

Estimates are derived for carrier lifetimes in the compounds due to a process of direct electron-hole recombination with emission of a single photon. Existing optical absorption data were used; the recombination notes were calculated from the formula of van Roosbroeck and Shockley. The values given are, for PbSe 0.6×10^{-6} sec, PbTe 0.8×10^{-6} sec, and PbS 40×10^{-6} sec, the errors were estimated at factors of 2, 3, and 5, respectively.

56. Madsen, P.E.

THE CALIBRATION OF THERMOCOUPLES UNDER IRRADIATION IN BEPO. AERE-M/R-649, 21p., 25 Jan 51.

The thermo-electric emf of a chromel-alumel thermocouple at the freezing points of tin and lead and of iron-constantan, copper-constantan and platinum-platinum/13% rhodium thermocouples at the freezing point of lead have been measured in BEPO. Of the four couples investigated at the freezing point of lead, the platinum-platinum/13% rhodium couple gave the most reproducible behavior and no significant change in the couple reading was introduced by irradiation. The other couples all showed significant increases, chromel-alumel giving the biggest effect, i.e., 1.1°C. At the freezing point of tin, chromel-alumel showed no significant change at first but on prolonged irradiation gave a statistically significant decrease of 0.47°C. In all the couples, the mean of the readings when the pile was working was significantly different from when it was shut down, but this effect was small except for the chromel-alumel couple at 327°C when it was about 0.5°C.

57. Martin Company, Nuclear Div., Baltimore, Md.

BIBLIOGRAPHY OF SNAP REPORTS. MND-P-2413, Aug 60, 9p. (Contract AT(30-3)-217)

A listing is presented of documents, films, slides, and those items which were formally produced for utilization by the AEC concerning the SNAP project.

58. Martin Company, Nuclear Div., Baltimore, Md.

SNAP PROGRAMS. Quarterly progress rept. no. 1, 22 Oct - 31 Dec 1959; MND-P-3009-1, Nov 60, 287p. (Contract AT(30-3)-217)

An analysis was made of the SNAP III generator to determine the cause of failure, and the test specifications were revised in line with the findings. During calibration and demonstration runs with the SNAP III-A generator, a leak developed in the valving mechanism of the variable heat-dump system. An examination disclosed that the valve was not satisfactory, so the generator was returned to the manufacturer for repair. A description is given of the generator, along with a performance evaluation program. A discussion is given of the work performed in advancing the technology of thermionic converters, specifically to increase efficiency by developing better emitter and

58. (cont'd) and collector materials and by reducing heat losses. Investigations were made in the areas of cesium diodes, effects of cesium on materials, electrical heaters, diffusion of gases through metals, and work function tests. Work done on the development of low-power thermionic generators included prototype development, heat-transfer studies and tests, vacuum tests in prototype shells, cathode and sapphire creep tests, a parametric study, the development of molybdenum fuel capsules, heliarc welding of molybdenum fuel capsules, hazards studies on Ce^{144} thermionic units, fabrication of a containment cask for Ce^{144} units, and fueling molybdenum capsules with C^{144} pellets. Investigations were made of the operational capabilities of SNAP-III type generators through tests simulating the anticipated environments to obtain information for conceptual designs to produce 2 to 5 watts of electrical power. Accomplishments in the development of a 1-watt nuclear power supply include the establishment of the over-all generator configuration, the sizing and arrangement of the Pu^{238} fuel, the analysis for helium pressure build-up within the fuel capsule, the selection and sizing of thermoelectric elements, a radiator design, the insulation arrangement, and the thermal analysis of the configuration. Work performed on the conceptual design of a 100-watt thermoelectric generator was devoted to heat-transfer analysis, isotope requirements, basic configuration design studies, selection and optimization of thermoelectric generator parameters, radiation shield design, evaluation of fuel containment problems under conditions of helium evolution, and the measurement of thermoelectric materials data. Analyses of heat-transfer and radiation shielding and studies of generator and component designs resulted in an optimum configuration for a 13-watt generator of the radiative-cylindrical type. The weight of the generator, exclusive of voltage regulation equipment, is 8.6 lb; the over-all efficiency is 6.2%. Fuel-technology development studies were directed toward a parametric study of radioisotopes suitable for isotopic power, the feasibility of processing the selected isotopes, and the selection of purification procedures.

59. Martin Company, Nuclear Div., Baltimore, Md.

SNAP PROGRAMS. Quarterly progress rept. no. 3 for 1 Apr through 30 June 60; MND-P-3011, 162p. (Contract AT(30-3)-217)

Design studies were made for the cooling, shielding, and electrical-control support systems required for the testing of the isotope-fueled 125-w generator in a hot-cell facility. A ceric oxide fuel containing 10 wt. % SiC exhibited suitable burn-up characteristics in simulated postorbital re-entry heating conditions. Inconel X was selected as the fuel-containment material. Negative pitch angle injections were evaluated for the injection-stage flight vehicle. The second electrically heated 125-w generator was assembled and prepared for checkout. A successful reproducible process for bonding the p element was developed in which GeTe was furnace melted into an iron shoe and a spring-loaded element was bonded to the shoe in an induction furnace.

59. (cont'd) The p element contact resistance was 0.1 milliohm. The maximum output on the first generator was measured as 78.2 w. Measurements were stopped when power output deteriorated to 28.8 w. An inspection showed that oxidation due to insufficient reducing atmosphere at the hot junction contacts was the cause. Parametric thermoelectric generator performance tests were conducted in which the internal gas pressure was varied from 0 to 1.5 atm. and the external pressure was either 1 atm. or a vacuum. The fabrication, operation, and performance of esium diodes were studied. The effect of a molybdenum powder film on heat transfer when placed in a molybdenum-tungsten interface was determined. In development studies on a low-power thermionic generator, cathode and sapphire-support creep tests were conducted up to 500°C, at which temperature no creep was observed. The design of Generator 2A was completed. A heater was developed for the generators which is capable of simulating the power density of a Cm^{242} heat source. A titanium alloy, A-70, was found which possessed satisfactory properties for use as a lead-through at 1050°C. A method of electrically insulating the two stages of a generator was developed. Tests were performed which showed that no interaction takes place between Ce_2O_3 and molybdenum in an oxygen atmosphere at 1600°F. Methods for removing aluminum from a curium capsule by volatilizing in either bromine or chlorine was were investigated. An analysis to determine the helium pressure build-up in aluminum-americium capsules was conducted. Dose rates were determined for americium slugs betore irradiation at distances from the slug surface up to 1 m. An evaluation of the effectiveness of the curium shipping cask was made. The power release by decay products of Pu^{236} and U^{232} was determined. Equations are presented concerning the reaction kinetics involved in the neutron irradiation of Am^{241} with the subsequent production of Cm^{242}.

60. Martin Company, Nuclear Div., Baltimore, Md.

SNAP RADIOISOTOPE SPACE PROGRAMS, TASK 2,

3, AND 7. Quarterly progress rept. no. 5,

1 Oct through 31 Dec 60; MND-P-3013-1, 46p.

(Contract AT(30-3)-217)

Functional testing was completed on the ground handling equipment for transporting the Ce^{144} heat source container and loading the SNAP 1A generator. Mercury shield fill and drain tests for the generator system and the collar shield were conducted. Heat-transfer tests of the isotope heat source shipping cask were conducted. Simulated rocket-launch environmental tests of vibration, acceleration, and shock were completed on the G-2 generator. Analysis of the environmental test data was initiated. Final design studies for the G-3 generator were completed, and a thermoelectric module concept was selected for use in the isotope-fueled generator. Development tests of thermoelectric modules in a module tester were initiated. Voltage break-down tests were conducted on a porcelain enamel spray coat. The material was

60. (cont'd) evaluated for application to the G-3 generator inner skins as a possible second discrete barrier against hot junction electrical shorts. SNAP 3 generator 3M-1G10 completed 322 days of life test operation and the power input was terminated after the generator was operated under a full range of external loads to obtain performance characteristics. Electrical power output after 322 days at steady-state heat source and external load conditions was 1.92 watts, for an over-all efficiency of 2.9%. Tear-down inspection of the generator confirmed previous indications of increased internal electrical resistance and thermal conductivity, which account for the gradual reduction in generator performance from the start-of-life electrical output of 3.45 watts and 5.2% over-all efficiency. The SNAP 3 3M-1G5 generator was successfully fueled with Po^{210}. Maximum electrical power output was 4 watts at an over-all efficiency of 5.2%. Radiological safety studies for space power were initiated.

61. Myers, M.N.

IRRADIATION STUDY OF PLATINUM AND

PLATINUM-RHODIUM THERMOCOUPLE WIRE.

DC-58-5-730, 28 May 58, 4p.

The results indicate that the Ir^{192} arises principally from an (n, gamma) reaction by thermal neutrons on an Ir^{191} impurity in the thermocouple wires and that this impurity is much larger (three times) in the Pt - Rh wire than in the Pt wires tested. The ratio of impurity seems to vary from wire to wire. The new Pt - Rh wire was much more active than the used wire. Since exact MTR flux measurements were not calculable from this irradiation, quantitative values of the total amount of iridium impurity present cannot be given.

62. Nobe, K., Miniato, O.K. and Seyer, W.F.

Stress and electro-potential of copper

wires. AM. INST. MINING ENGRS. MET. SOC.

TRANS., v. 212, p. 884-889, 1958.

The emf produced by applying a tensile stress, σ, to one of a pair of electrolytic (99.92%) Cu wires in M-NaCl and 0.1 M-$CuSO_4$ solution was measured under restricted-flow conditions. For annealed Cu within the region where Hooke's law applies, emf $\propto \sigma^2$, as predicted by theory, and the process is reversible, while for cold-worked material, emf $\propto \sigma$, and again the process is reversible. Where σ is sufficient to cause plastic deformation the emf decreases, and

62. (cont'd) the process is irreversible. The results are discussed in relation to thermodynamical considerations.

63. Nuclear energy in space. NUCLEONICS, v. 19, n. 4, p. 53-100, Apr 1961.

High- and low-thrust missions and those requiring high auxiliary power levels are discussed. Strategies of design and operation for reducing danger to populations are also considered. Radionuclide SNAP units provide durable, continuous electric power sources from 1 to 100 w with predictable lifetimes. Uses of SNAP units are discussed. KIWI-B ground tests with flight configurations are described. Problems of high-temperature reactor fuels and engine control during quick startup are investigated. Environmental problems of spacecraft, including particle bombardment, heat flux variations and ultra-high-vacuum materials problems are detailed. Uses of gaseous- and solid-fuel reactors, along with methods for separating propellants and fuels, and the use of atomic explosion propulsion are described.

64. Oak Ridge National Lab., Tennessee. GAS-COOLED REACTOR PROJECT SEMIANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1958. Rept. no. ORNL-2676, 16 Mar 59, 176p.

The program is divided into two principal parts: design investigations and materials research and testing. Most of the activities described were initiated in support of the prototype gas-cooled power reactor (GCPR) designed by Kaiser Engineers-ACF Industries. Some advanced reactor design studies were made, and basic design studies required to facilitate design review work were completed that have application beyond the limited review objective. In furtherance of an assigned responsibility for providing the fuel elements for the GCPR, methods for fabricating and testing fuel elements were developed. Tests of mechanical properties were undertaken as required to obtain the information needed in the development of the fuel elements. In-pile and out-of-pile tests of the components and materials of the reactor core were also initiated.

65. Oak Ridge National Lab., Tennessee.

INSTRUMENTATION AND CONTROLS DIVISION

ANNUAL PROGRESS REPORT FOR PERIOD ENDING

JULY 1, 1959. Rept. no. ORNL-2787, 2 Nov 59,

152p.

Instrumentation and controls development for various projects is summarized. Among the items reported on are a 2048 channel neutron time-of-flight analyser, a versatile instrument camera with a microsecond electronic shutter, grid current in electrometer tubes, personal radiation monitor, systems analysis, additions and modifications to the instrumentation of the Fission Products Pilot Plant, instruments and controls for the Maritime Ship Reactor pressurized water experiment in the ORR, and Homogeneous Reactor Project instrumentation and controls.

66. Palladino, N.J.

INFORMATION PERTAINING TO THE USE OF

THERMOCOUPLES IN HIGH NEUTRON FLUX.

Westinghouse Atomic Power Div. 24 May 54,

2p.

Results are reported from tests of the effect of neutron flux on thermocouple calibration and on thermocouple insulating materials which indicate that a high neutron flux has no appreciable effect on the thermoelectric properties of a thermocouple but that irradiation does have an adverse effect on the insulation properties of most materials. To date the materials that have proved to be the most satisfactory insulation materials are magnesium oxide, aluminum oxide, lava, and a ceramic insulation material.

67. Peschke, K.

Thermoelements and thermoelectric DC generators.

ARCH. ELEKTROTECH., v. 43, p. 328-354, 29 Nov

1957. (In German)

"Detailed theoretical investigation of thermodynamic efficiency taking account of the various thermoelectric effects, and changes in resistivity and thermal conductivity. Higher efficiencies should be obtainable than those

67. (cont'd) indicated by other authors. Problems of construction and mechanical strength are also considered."

68. Pikus, G.E.

Thermo- and galvanomagnetic effects in semiconductors taking account of variations in carrier concentration. I. Thermo- and galvanomagnetic effects in weak fields.

ZHURN. TEKH. FIZ., v. 26,p. 22-35, 1956.

(In Russian)

Extensive calculations taking account of recombinations in the bulk and at the surface for some simply shaped specimens when the fields are so weak that the carrier concentration is only slightly different from its equilibrium value. The following effects are discussed: thermoelectric power, Hall effect, magneto-resistance, electrical resistance in a temperature gradient, the Ettingshausen effect, and behavior in oscillating fields.

69. Pikus, G.E.

Thermo- and galvanomagnetic effects in semiconductors taking account of variations in carrier concentration. II. Galvanomagnetic effects in strong fields. Thermal conductivity of electrons and excitons. ZHURN. TEKH. FIZ., v. 26, p. 36-50, 1956. (In Russian)

Continuation of Part I. Treats electrical conductivity, Hall effect, magneto-resistance, electronic thermal conductivity and the transport of heat by excitons.

70 Pohl, R.G.

Electrical properties of beta silicon carbide In SILICON CARBIDE. A HIGH TEMPERATURE SEMICONDUCTOR. PROCEEDINGS OF THE CONVERENCE, BOSTON, 1959. New York, Pergamon Press, J.R. O'Conner and J. Smiltens, eds , p. 312-330, 1960

Part II is of particular interest It is concerned with measurements of resistivity, Hall effect, lifetime thermal activation energy, and thermoelectric power

71. Pollak, P.I.

STRUCTURAL INVESTIGATIONS IN THERMO-ELECTRIC MATERIALS. Merck Sharp and Dohme Research Laboratories, Rahway, N.J. Progress rept. 1, July 60, 9p. (Contract Nobs-78503) ASTIA AD-245 073

The report describes work on the thermoelectric alloy $Bi_{24}Sb_{60} + x\ Se_6\ Te_{50-x}$. A historical introduction is followed by the description of the x-ray diffraction work which has led to the establishment of the dimensions of the super symmetry and probably assignment of a space group. Stoichiometric analysis of the superstructure unit cell suggests the existence of antimony in both the 3 and 5 oxidation states This variable makes the alloy a poised system and permits in principle the investigation of twenty integral alloys ($-8 < x < 12$). To date the most interesting compositions with figures of merit in excess of $3 \times 10^{-3}\ K^{-1}$ have been found in the range $6 < x < 8$ Methods of preparation and crystalization are described

72 Reid, F.J.

THE EFFECT OF NUCLEAR RADIATION ON SEMICONDUCTOR DEVICES. Radiation

72. (cont'd) Effects Information Center, Columbus, Ohio. Rept. 10, 30 Apr 60, 26p. (Contract AF33(616)6564) ASTIA AD-240 433

The current state of the art on the effects of nuclear radiation on semiconductor devices is presented. What information is available is presented on thermoelectric devices.

73. Rosi, F.D., Hockings, E.F. and Lindenblad, N.E. Semiconducting materials for thermoelectric power generation. RCA REV. (USA), v. 22, n. 1, p. 82-121, Mar 1961.

A general consideration of the thermoelectric properties of semiconductors suggests that (1) this class of materials can be useful in power-generating thermocouples operating at least up to 700°C, and (2) use of a sandwich-type arrangement or graded alloying in the construction of thermocouple branches will be necessary to achieve high figures of merit over a wide temperature range and, hence, high power-generating efficiencies. A large number of ternary compound semiconductors having the cubic structure were synthesized. Those with the rock-salt structure, such as $AgSbTe_2$, are characterized by low lattice thermal conductivities (< 0.0075 W cm^{-1} deg^{-1}). The lattice thermal conductivity as a function of composition was examined in the alloy systems of $AgSbTe_2$ with PbTe, SnTe, and GeTe. The minimum in the lattice thermal conductivity for the $AgSbTe_2$-PbTe system gives an effective mean free path for phonons which is less than unit-cell dimensions. Measurements of the temperature dependence of thermoelectric properties of a number of solid-solution alloy systems showed that (1) solid-solution alloys of Bi_2Te_3, with Bi_2Se_3, Sb_2Te_3, and Sb_2Se_3 provided the best p- and n-type material for thermocouple operation in the temperature range 25 to 250°C, (2) the ternary compound $AgSbTe_2$ and its alloys with GeTe provided the best p-type material for the range 250 to 550°C, and (3) alloys in the PbTe-SnTe system provided the best n-type material for the range 250 to 550°C. Power-generating thermocouples constructed in the sandwich-type arrangement of materials, provided an efficiency of ~12% for operation over the temperature range 20 to 550°C (i.e., T_H-T_C =530°C). Continuous thermocouple operation for 300 hr resulted in no significant deterioration of material properties.

74. Savornin, J. and Savornin, F. Discontinuities in the thermoelectric properties of thin metallic films.

74. (cont'd) C.R. ACAD. SCI. (Paris), v. 240, n. 8, p. 850-2, 21 Feb 1955. (In French)

Continuing previous work the thermoelectric power of thin films of aluminum was studied. As the temperature of the hot junction was raised the film gave the same results as a thick sheet up to about 100°C, after which the thermoelectric power increased rapidly. On lowering the temperature and repeating the experiment, the temperature at which the abnormal increase set in usually became progressively higher. Though e experiments were conducted in air, there is reason to think the effect is not due to oxidation. Further work is in progress.

75. Savornin, F. Influence of thickness on the thermo-electric power of thin films of aluminum and cobalt. C.R. ACAD. SCI. (Paris), v. 245, n. 2, p. 147-9, 8 July 1957. (In French)

The thermoelectric power of thin films of Al heated after deposition increases because of superficial oxidation. The thermoelectric power of Co films increases with increasing thickness but the effects of oxidation are less severe.

76. Schock, A. Effect of magnetic fields on thermionic power generators. J. APPL. PHYS., v. 31, p. 1978-1987, Nov 1960.

It is demonstrated that the high currents present in large thermionic power generators produce magnetic fields which result in a considerable reduction of electron transmission and energy conversion efficiency. To overcome the adverse effect of the self-induced field, the report presents the concept of a magnetothermionic power generator, employing an externally produced magnetic field parallel to the current direction. Analysis indicates that this concept will permit efficient operation of large generators. In addition, by use of a modulated field coil current, it offers the possibility of the direct generation of alternating current, at a controlled frequency.

77. Stourac, L.

Effect of ageing on the electrical properties of the semiconducting system Bi_2Te_3-Bi_2Se_3. CZECHOSLOV. J. PHYS., v. 9, p. 717-720, 1959. (In Russian)

It is shown that the change in electrical conductivity and thermoelectric force are caused by the change in concentration of the free electrons. The effect of this process on the efficiency of equipment employing the Peltier effect is analyzed.

78. Taraba, F.R. and Paine, S.H.

Effect of neutron irradiation on the thermoelectric emf and electrical resistivity of metals and alloys. In ARGONNE NATIONAL LABORATORY ANNUAL REPORT FOR 1958. Lemont, Ill., p. 109-119, Mar 1959.

Includes a schematic diagram of a thermoelectric circuit used to measure average thermoelectric power.

79. Thermoelectric generator undergoing test. ELECTRON., v. 33, p. 11, 8 July 60.

"Lightweight generator designed to power space probes and satellites for periods of a year or more is undergoing tests at Martin's Baltimore laboratories. Named SNAP-1A (system for nuclear auxiliary power), the power system is intended to put out more electricity for longer periods than other power units developed for space vehicles. The thermoelectric device uses a tightly sealed Inconel-X capsule filled with spontaneously decaying cerium-144 pellets. Heat from the decay of the Ce-144 is directly converted into electricity by a lead telluride sheath surrounding the capsule. The egg-shaped power supply is 3 ft. long, weighs 175 lb., can produce 125 w at 28 v d-c continuously for a year, Martin spokesmen say. To shield the spaceprobe ground crew prior to launching, the egg is filled with two tons of mercury which is drained out five seconds before firing."

80. Tyler, W.W.

ELECTRON THEORY OF THERMOELECTRIC EFFECTS. Rept. KAPL-M-WWT-1, Sep 51, 17p.

Expressions are derived which permit the rough prediction of changes in calibration of various thermocouples due to neutron damage Several generalities are proposed regarding these changes.

81 Uhlmann, W.

RADIATION EFFECTS IN THERMOCOUPLES - BIBLIOGRAPHY. (Strainingseffekter i Termoelement - Bibliografi). Aktiebolaget Atomenergi, Stockholm. 14 Sep 60, 5p

A bibliography of 13 selected references to report and published literature on radiation effects in thermocouples is presented.

van Lint, V.A.J. and Roth, H.

High-energy electron irradiation of germanium and tellurium. JOURNAL OF APPLIED PHYSICS, v. 30, n. 8, p. 1235-1238, Aug 1959.

Tellurium samples in which current flowed parallel to the c-axis were irradiated at 78°K with 20-Mev electrons N-type germanium was irradiated with 20-Mev electrons at room temperature Conductivity measurements indicated that the sample became intrinsic and then p type.

83 Wenden, H.E., Zaidi, R.A. and Shevlin, T.S.

THERMOELECTRIC MATERIALS, MARCH 1 - APRIL 30, 1960. Ohio State University Research Foundation, Columbus, Ohio. Rept. 1039-2, 4 May 60, 5p. (Contract Nobs-78254)

83. (cont'd) Concerns the effect of oxidizing and reducing atmospheres on the emf produced by Na_2O; $6V_2O_5$ referred to a NV_6.

84. Westinghouse Electric Corp., Research Labs., Pittsburgh, Pa.

FIVE KILOWATT THERMOELECTRIC GENERATOR.

Bimonthly progress letter no. 1, 12 May 59, 52p. (Contract Nobs 77093) ASTIA AD-225 605

Design of thermoelectric material configurations and environmental checking of thermoelectric elements are described. Life data on Bi-Te and ZnSb were obtained at 400°C to 1000 hrs. Tests on other materials are beginning. A Datatron computer program was constructed to calculate sandwich element geometries for various generator conditions.

85. Westinghouse Electric Corp., Pittsburgh, Pa.

THERMOELECTRIC NUCLEAR FUEL ELEMENT.

Quarterly rept. no. 1; WCAP 1245, 10 July 59, 30p. (Contract AT-(30-3)-500)

Samples of the following materials were prepared for irradiation testing: $Li_{.013}Ni_{.987}O$ and $Li_{.035}Ni_{.965}O$; $La_{.1}Ba_{.9}TiO_3$; $Bi_{.05}Ge_{.95}Te$; GeTe, MnTe; CeS_x and $CeSe_x$. On the basis of present data, all materials have sustained radiation damage at the temperature of exposure in the reactor. The radiation damage begins to anneal out for most materials at fairly low temperatures as shown by the post-irradiation measurements.

86. Wilson, V.C.

ELECTRIC ENERGY SOURCES AND CONVERSION TECHNIQUES FOR SPACE VEHICLES. General Electric Research Laboratory paper 60-31 presented at the IAS 28th Annual Meeting, New York, Jan 25-27, 1960.

86. (cont'd) Electric generators for space vehicles must be dependable, have long life and be light weight. If the generator is a heat engine and thus requires radiating away unused heat, it must be a high temperature heat engine. This paper investigates and discusses thermionic converters in relationship to requirements for space vehicle electric generators.

87. Witzig, W.F.

WAPD - 1 EXPERIMENTS IN THE MATERIALS

TESTING REACTOR. I. GAMMA HEATING WAPD-1-1.

Rept. WAPD - 79, Mar 53.

....The feasibility of conducting experiments in the active lattice of the MTR using bottom entry has been demonstrated by the gamma heat experiment. In this experiment, chromel alumel thermocouples have been to 1425 megawatt days of irradiation without permanent damage within a precision of $\pm$ 0.2°C.

88. Yockey, H.P.

Use of thermocouples in a radiation

field. PHYS. REV., v. 101, p. 1426,

15 Feb 1956.

The radiation damage effects on an iron-constantan thermocouple are briefly discussed. It is concluded that such thermocouples give satisfactory temperature indication for most radiation field applications.